U.S.A. Visibility Monitoring, Trends, and Regulatory Programs and Their Relevance to Korea

Scott F. Archer
U.S. Department of the Interior, Bureau of Land Management
National Science and Technology Center, Denver, Colorado 80225, U.S.A.
scott_archer@blm.gov
and
Kyong C. Chun
Argonne National Laboratory, Environmental Assessment Division
Washington, DC 20024, U.S.A.
kcchun@anl.gov

Abstract

This paper describes visibility monitoring and regulatory programs in the United States, particularly within certain designated National Parks and Wilderness Areas. Government agencies responsible for the management of federal lands, in cooperation with other federal, state, and regional air quality organizations, have established a monitoring program of more than 125 sites. Recent visual documentation (scene images), optical measurements, and aerosol characterizations (mass and chemical speciation) obtained at selected monitoring sites are presented, as information on general spatial and temporal visibility trends. National regulations are described that limit the amount of additional visibility impairment from new or modified emission sources and that establish a schedule for improving existing conditions in designated areas. The relevance of the experience in developing and implementing these programs to the planning for programs to address emerging visibility problems in Korea is discussed.

1. Introduction

> "The quality of urban air compared to the air in the deserts and forests is like thick and turbulent water compared to pure and light water. In the cities with their tall buildings and narrow roads, the pollution that comes from their residents, their waste makes their entire air reeking and thick, although no one is aware of it." – Moses Maimonides (1135-1204) [1].

The relationship between polluted air and impaired visibility has been known, and commented upon, for centuries. As stated by the U.S. Environmental Protection Agency (U.S. EPA), "from a scientific and technical point of view, deterioration of visual air quality is probably the best understood and most easily measured effect of air pollution" [2]. However, visibility has only recently become a subject of systematic measurement and, on a limited basis, regulation.

Military and aviation interests were the first to regularly measure and report "visual range" conditions, particularly at airports, so that pilots would know when to expect to see landing runways. "Visual range" is typically defined as the greatest distance a dark object may be differentiated from its background sky.

In 1977, the U.S. Congress established a national visibility goal for "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from manmade air pollution" [3]. These areas consist primarily of large national parks and wilderness areas located in 36 of the 50 states (Figure 1).

On the basis of this national goal, reliable quantitative measurement devices, predictive modeling methods, and enforceable regulations have been developed during the last twenty-five years.

2. Vision through the atmosphere

When an observer views a distant object, such as tall buildings or a mountain peak, light from the object is reduced in proportion to the amount of air pollution in the atmosphere. In addition, light from the sun will be added to the view, either directly by or reflection from clouds or the earth's surface. The amount of light that is attenuated (altered) per unit distance can be represented by the total extinction coefficient, or b_{ext}. This total light extinction is made up of the absorption of light by particles (b_{ap}) and gases (b_{ag}), and the scattering of light (out of and into the sight path) by particles (b_{sp}) and gases (b_{sg}):

$$b_{ext} = b_{ap} + b_{ag} + b_{sp} + b_{sg}$$

where

- b_{ap} is dominated by elemental carbon particles (or soot).
- b_{ag} is primarily caused by nitrogen dioxide gas, which usually is not significant unless located near large oxides of nitrogen emission sources, but may cause a view to appear reddish because the gas preferentially absorbs blue light.
- b_{sp} is usually the single largest contributor to visibility reduction (except under very clean conditions), caused by both primary (directly emitted) and secondary (chemically converted from gases such as sulfur dioxide and nitrogen dioxide) particulate matter. Fine particles (from 0.1 to 1.0 micrometers in effective diameter) are the most efficient at scattering visible light.
- b_{sg} is caused by the preferential scattering of blue light of natural air molecules and is also known as Rayleigh scattering.

The total extinction coefficient can be related to "visual range" (*VR*) as follows:

$$VR = 3.912 / b_{ext}$$

Assuming the following: the object is black (with an inherent contrast of -1.0); there is uniform sky illumination from the object to the viewer; and the apparent contrast limit (just detectible difference) is 2 percent.

However, the "visual range" metric is inconvenient when comparing visibility changes in different areas. For example, a 10 kilometer change in "visual range" is much more noticeable under polluted conditions (e.g., a reduction from 30 kilometers to 20 kilometers) than under clear conditions (e.g., a reduction from 300 kilometers to 290 kilometers).

For this reason, Pitchford and Malm (1994) developed a standard visual index "designed to be linear with respect to perceived visual changes over its entire range in a way that is analogous to the decibel scale for sound" [4].

Their deciview (*dv*) index is related to total extinction (b_{ext}) as follows:

$$dv = 10 \times \ln (b_{ext} / 0.01 \text{ km}^{-1})$$

where b_{ext} is expressed in km^{-1} (inverse kilometers) and it is assumed that objects are visible at distances sensitive to visual changes (e.g., neither too close nor too far away from the observer).

As stated by the authors, "a 1 *dv* change is about a 10% change in extinction coefficient, which is a small but perceptible scenic change under many circumstances." In addition, this difference will be equally noticeable under clear or polluted background conditions.

Using the WinHaze Visual Air Quality Modeler software system, Figure 2 compares a 10-kilometer change in "visual range" under clear and polluted conditions, and a 10 percent change in total extinction (a 1.0 *dv* change) under similar conditions [5].

Both Malm [6] and Trijonis, *et al.* [7] elaborate on the relationship between air pollution and visibility.

3. Visibility monitoring

Historically, the National Weather Service has used human observers to characterize hourly "visual range" conditions at U.S. airports. Although these data are useful in providing long-term general trends in visibility, variability among observers and targets (including size, color, and distances) limit the precision of quantitative data.

Early studies to quantitatively measure optical conditions included using photographic documentation and teleradiometers to routinely measure apparent contrast, nephelometers to measure optical scattering of sampled air, and transmissometers to measure total extinction through the atmosphere over relatively short path lengths.

In 1985, the U.S. EPA, the Bureau of Land Management, the Forest Service, the National Park Service, and the U.S. Fish and Wildlife Service established a long-term visibility monitoring program called IMPROVE (Interagency Monitoring of PROtected Visual Environments) [8]. The program has expanded to include state and local air quality regulatory agencies and associations.

Monitoring methods include photographic records of visual conditions (using either 35-millimeter film or digital images), direct optical measurements (using either ambient temperature nephelometers or long-path transmissometers), and aerosol samplers to determine the concentration and chemical composition of visibility-impairing pollutants. Currently, IMPROVE network monitors (or similar monitors operated using IMPROVE protocols) are located at nearly 125 locations throughout the United States.

4. Visibility trends

Trends of mass and chemical composition from 29 IMPROVE aerosol samplers have been derived for the period 1988 through 1998 [9]. These data may be interpreted as "reconstructed visibility" as described in Section 6 (analysis methodology) below. Although most long-term sampling has been conducted in the western United States, some interesting national trends are evident (Figure 3).

For the cleanest aerosol samples (the "best" 20 percent of the data base), statistically significant improvements in reconstructed visibility (interpreted as *dv*) have occurred at 20 of the 29 locations. Over the 10-year period, these improvements would be perceptible (greater than a 1.0 *dv* change) at 18 locations. Of those sites analyzed, the greatest improvement in visibility on clean days has been at Mount Rainier National Park, located in the Pacific Northwest.

For the dirtiest aerosol samples (the "worst" 20 percent of the data base), statistically significant improvements in reconstructed visibility have occurred at ten locations. Over the 10-year period, these improvements would be perceptible at nine locations, including those areas with the most improvement (Shenandoah and Acadia national parks in the northeastern United States).

However, these "worst" days have further degraded at five locations, with perceptible changes at Yosemite National Park in California and Guadalupe Mountains and Big Bend national parks in western Texas.

A recent study by Malm, *et al.* (2002) has examined ammonium sulfate aerosol trends throughout the United States over two time periods: 1990 through 1994, and 1995 through 1999 [10]. Ammonium sulfate is one of the most significant contributors to visibility degradation. Of nearly 75 locations analyzed, statistically significant reductions in ammonium sulfate concentrations were observed at nearly 25 locations in the northeastern United States on both the "best" and "worst" days. In addition, only three locations (in northern California, western Texas, and western North Carolina) demonstrated significant increases in ammonium sulfate, and those occurred only on the "worst" (dirtiest) days.

In general, the analysis shows minor changes in ammonium sulfate concentrations in the western United States, but significant reductions in the northeastern United States (up to 10 percent during summer months). These lower concentrations are probably a result of sulfur oxide emission reductions throughout the Ohio River Valley and are also likely to result in improved visibility.

5. Visibility regulations

Although the opacity of visible smoke plumes from industrial facilities have been regulated in Europe and the United States since the late 19th century [11], comprehensive visibility protection for selected locations was not established in the United States until 1977.

With establishment of the national visibility goal, the U.S. EPA developed regulations to protect and improve visibility in 158 mandatory federal Class I areas. As specified by the Clean Air Act, these areas (which were in existence on August 7, 1977) include all international parks, national wilderness areas exceeding 5,000 acres, national memorial parks exceeding 5,000 acres, and national parks exceeding 6,000 acres. The federal land management agencies subsequently determined that visibility was not an important value in two of these areas.

In 1980, the first phase of regulations required the 36 states that contained mandatory federal Class I areas to provide for protection and remediation of "plume blight" in those areas. This included direct impact of visible plumes, as well as other "reasonably attributable" impacts which could cause direct or indirect visibility impacts. These regulations focused primarily on large stationary sources of air pollution (i.e., coal-fired electrical generating stations, mineral-ore smelters, wood-product paper mills, etc.)

In 1999, the U.S. EPA established the "regional haze" regulations, designed to improve visibility impairment from a wide range of existing sources on a set schedule and to limit the amount of visibility impairment from new sources. In this case, all 50 states must develop methods to meet the national visibility goal, although they may create multiple state "regional planning organizations" to do so.

States are to collect visibility-related data from 2000 through 2004 to establish the "baseline" conditions. Then they are to determine a rate of visibility improvement for each mandatory federal Class I area (expressed in *dv*), evaluate visibility trends every 5 years, and revise their visibility implementation plans every 10 years [12]. The regulations require that all manmade visibility impairment within each mandatory federal Class I area be eliminated by the year 2064.

In addition, some state and local air quality regulatory agencies have also established their own visibility protection regulations, including California (minimum 10-mile *VR* during daytime hours), Colorado (wood-burning bans in the Denver metropolitan area when their Visibility Standard Index exceeds 100), and the Lake Tahoe Regional Planning Authority (achieve 171-kilometer *VR* during 50 percent of the year, and 97-kilometer *VR* during 90 percent of the year, based on aerosol measurements).

6. Analysis methodology

For the purposes of evaluating potential visibility impairment from proposed air pollutant emission sources, the Forest Service, the National Park Service, and the U.S. Fish and Wildlife Service have established their "FLAG" Phase I visibility impairment analysis methodology [13].

Visibility impairment from discrete plumes are analyzed using U.S. EPA steady-state, Gaussian-based plume dispersion models (i.e., VISCREEN [14] or PLUVUE II [15, 16]) to calculate the change in the color difference index (*)E*) and absolute value of contrast ($|C|$) between the plume and the viewing background (generally within 50 kilometers of the source). Based on refined impact analyses, values above $|C| = 0.02$ and *)E* = 1 would be the levels of concern.

For locations where visibility impairment is more likely to occur from "regional haze" (generally 50 kilometers or more away from the source), non-steady-state air quality dispersion models (e.g., CALMET/ CALPUFF [17]) with chemical transformation capabilities are used to predict the concentrations of visibility-impairing pollutants at each sensitive receptor.

The potential total extinction coefficient (expressed in inverse megameters or Mm^{-1}) is then calculated based on the following relationship:

$$b_{ext} \approx b_{SO4} + b_{NO3} + b_{OC} + b_{Soil} + b_{Coarse} + b_{ap} + b_{ag} + b_{Ray}$$

where:

$b_{SO4} = 3 \times [(NH_4)_2SO_4] \times f[RH]$
$b_{NO3} = 3 \times [(NH_4)NO_3] \times f[(RH]$
$b_{OC} = 4 \times [OC]$
$b_{Soil} = 1 \times [Soil]$
$b_{Coarse} = 0.6 \times [Coarse Mass]$
$b_{ap} = 10 \times [EC]$
$b_{ag} = 0.17 \times [NO_2]$
$b_{Ray} = 10\ Mm^{-1}$

- b_{SO4} includes a scattering extinction efficiency of 3, the ammonium sulfate concentration ($[(NH_4)_2SO_4]$), and a particle growth factor (f[RH]) based on the observed relative humidity.
- b_{NO3} also includes a scattering extinction efficiency of 3, the ammonium nitrate concentration ($[(NH_4)NO_3]$) and the particle growth factor (f[RH]).
- b_{OC} includes a scattering extinction efficiency of 4 and the "organic carbon" concentration ([OC]). Organic carbon aerosols may form due to volatile organic compound emissions.
- b_{Soil} has a unitary scattering extinction efficiency, and represents the "soil" (primary fine particulate matter) concentration ([Soil]), typically measured as particulate matter less than 2.5 micrometers in effective diameter.
- b_{Coarse} has a scattering extinction efficiency of 0.6, and represents the "coarse" particulate matter concentration ([Coarse Mass]), calculated as the fraction of particulate matter with effective diameter ranging from 2.5 micrometers to 10 micrometers.
- b_{ap} has an absorption extinction efficiency of 10 and represents the "elemental carbon" (soot) concentration ([EC]).
- b_{ag} has an absorption extinction efficiency of 0.17 and represents the nitrogen dioxide concentration ($[NO_2]$). The Rayleigh scattering component (b_{Ray}) is assumed to be 10 Mm^{-1} (at about 1,800 meters above sea level).

The "FLAG" visibility impairment analysis methodology compares calculated potential total extinction coefficient impacts to a set of established "natural background" extinction reference values for each mandatory federal Class I area. These reference values include annual and seasonal particle growth factors. If the calculated change in extinction is less than five percent (equivalent to 0.5 *dv*), then the federal land management agency "is not likely to object" to the proposed project. Alternatively, if the calculated change in extinction is greater than 10 percent (equivalent to 1.0 *dv*), then the federal land management agency "is likely to object." Between these two levels, the federal land management agency would "take a determination on a case-by-case basis taking into account the geographic extent, intensity, duration, frequency and time of visibility impairments."

7. Energy development example

During 2000, the Bureau of Land Management and Argonne National Laboratory began a study of potential air quality impacts associated with coal-bed methane development in northeastern Wyoming and southeastern Montana [18]. The analysis examined existing air quality conditions based on ambient monitoring data collected by the air quality regulatory agencies, private companies, and the federal land management agencies.

An inventory of potential emission sources that were not represented by the monitoring data was then prepared. This inventory included the proposed coal-bed methane development alternatives (predominately well construction and operation, as well as field and pipeline compressor engines) and other "reasonably foreseeable" emissions sources (including coal mine and railroad expansions and a new coal-fired electrical generating station).

The analysis team also obtained large-scale meteorological information, including 1995 MM5 global circulation model wind fields and regional weather station data. This information was synthesized with the CALMET preprocessor for use by the CALPUFF non-steady-state air quality dispersion model.

Finally, potential sensitive receptors, including mandatory federal Class I areas, were identified throughout the modeling domain (Figure 4). On the basis of this modeling analysis (the most extensive analysis of its kind to date), it was determined that all state and federal ambient air quality standards would be met (with a possible exception near a single existing coal mine), but that impacts to a single, very sensitive alpine lake could be above applicable thresholds.

Potential visibility impacts for sensitive receptors were first evaluated by comparing the calculated daily total extinction values to the assumed seasonal "natural background" reference levels using the "FLAG" visibility impact analysis methodology. Since these calculations exceeded the 1.0 *dv* threshold for at least one day at most sensitive locations, a refined analysis was then conducted comparing the calculated total extinction values to over 10 years of daily total extinction data measured directly with two regional transmissometers

The refined analysis showed that direct impacts from the maximum proposed development scenario could exceed the 1.0 *dv* visibility impact threshold on two days per year in the Bridger and Washakie mandatory federal Class I wilderness areas and on a single day per year in the

Fitzpatrick and North Absaroka mandatory federal Class I wilderness areas.

However, when combined with other “reasonably foreseeable” emission sources, the 1.0 *dv* visibility impact threshold could be exceeded up to 18 days per year in the Badlands and Wind Cave mandatory federal Class I national parks. The cumulative visibility impact analysis also examined other “sensitive receptors” which are not protected under the “regional haze” regulations, indicating up to 58 days could exceed the 1.0 *dv* visibility impact threshold on the Northern Cheyenne Indian Reservation.

8. Relevance to Korea

Like the United States, Korea faces increasing impacts to air quality and air-quality-related values (visibility and acid deposition) from domestic transportation and industrial sources. Efforts by the Korea Institute of Science and Technology [19], Y.S. Chung, T.K. Kim, and others [20, 21], including the recent international Asian Pacific Regional Aerosol Characterization Experiment [22], have documented the regional transport of aerosols into Korea. Korean scientists have also investigated the sources and effects of acidic aerosols (often called “acid rain”), but these same aerosols, once neutralized, form secondary fine particulate matter (ammonium sulfate and ammonium nitrate), which can have a significant impact on visibility.

Several Korean scientists have also been specifically investigating visibility impacts, including Y.S. Chung and T.K. Kim [23]; S.C. Yoon [24]; and K.W. Kim, *et al.* [25-27]. For example, the Kwangju Institute of Science and Technology is monitoring visibility in an urban environment, in order to understand the causes of visibility impairment, and to develop tools to predict visual air quality.

Perhaps the experience of development and field implementation of visibility monitoring and visualization techniques, collection and analysis of visibility data, and formulation and enforcement of visibility-related regulatory programs in the United States will be useful in planning for dealing with the emerging visibility problem in Korea.

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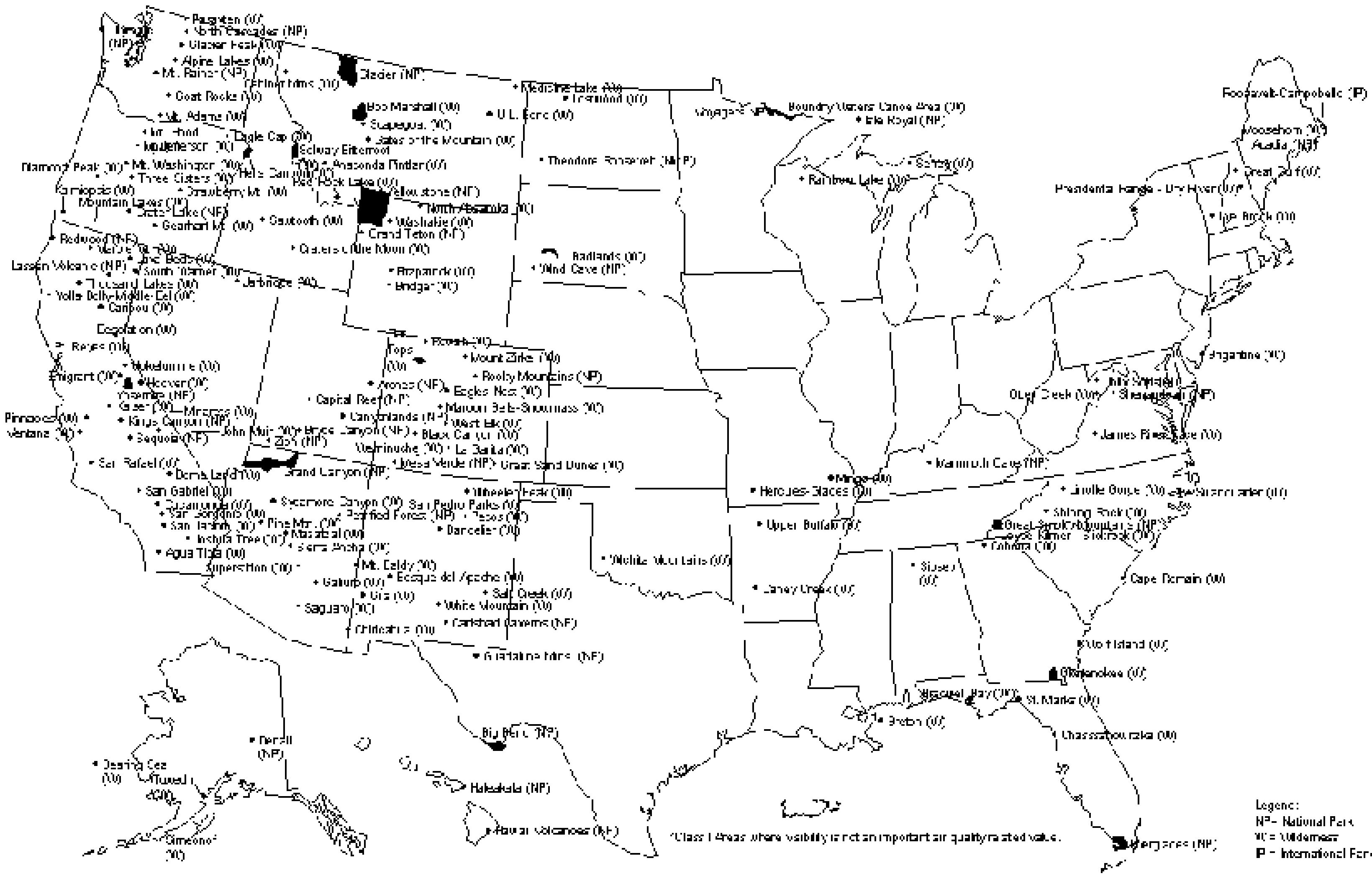

Figure 1. Mandatory federal Class I areas in the United States

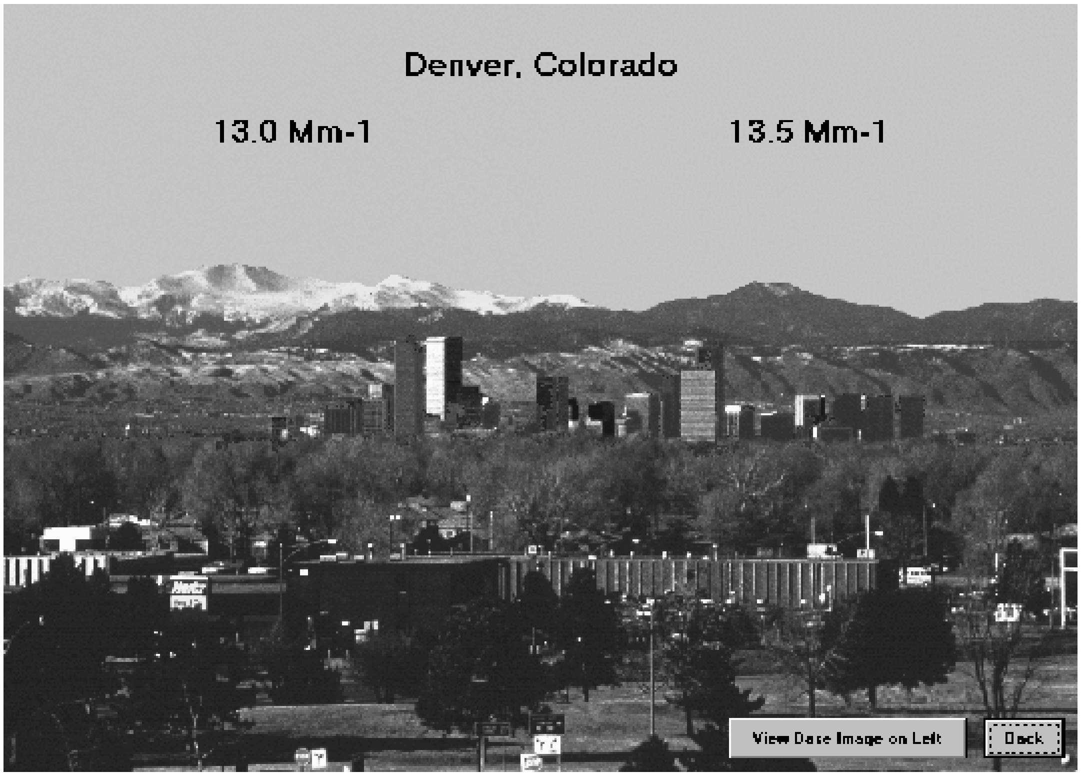

Figure 2a. Denver, Colorado, USA, "clear" day (from 300 to 290 km *VR*)

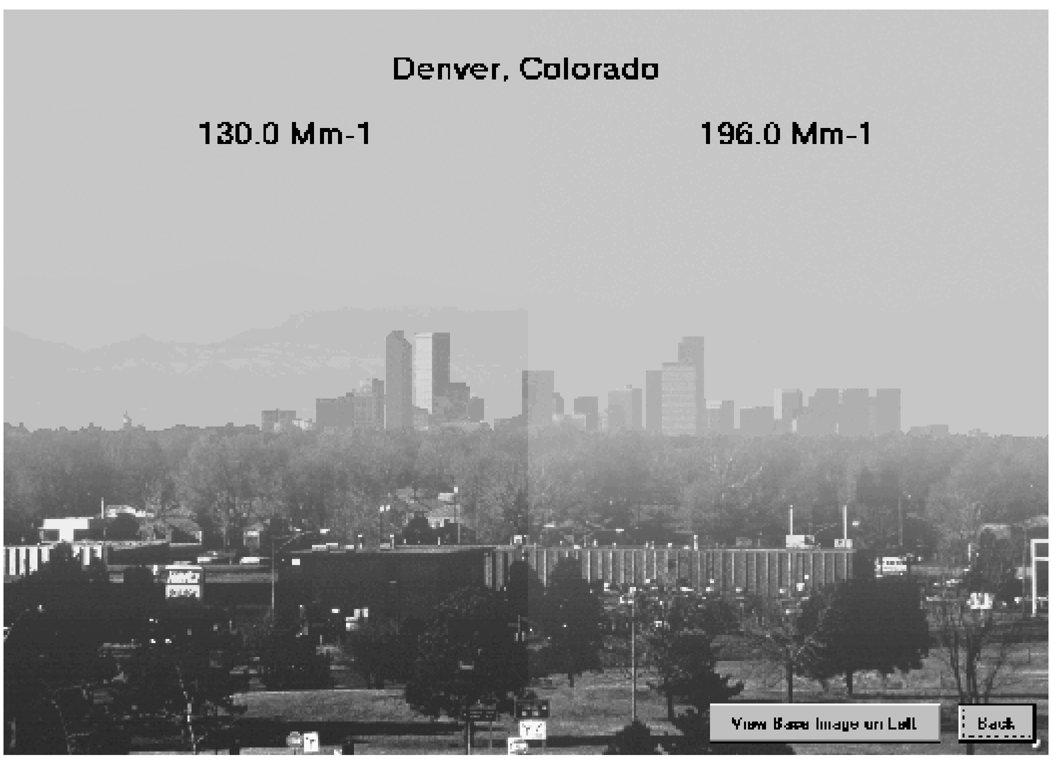

Figure 2b. Denver, Colorado, USA, "polluted" day (from 30 to 20 km *VR*)

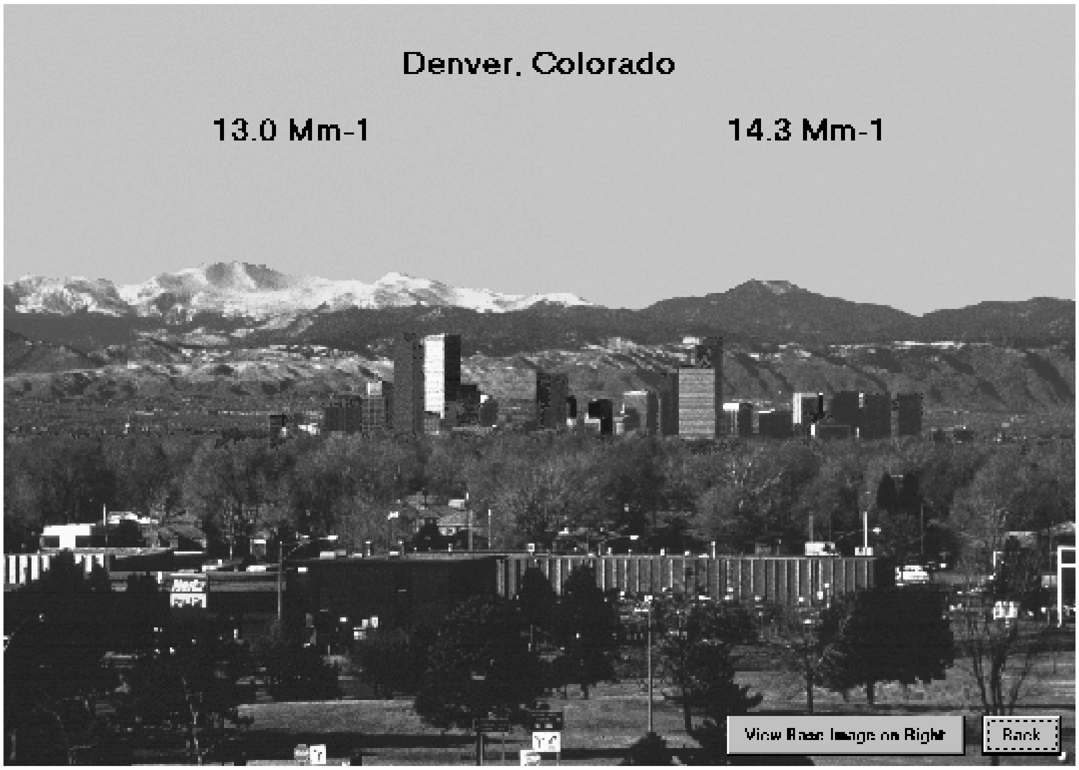

Figure 2c. Denver, Colorado, USA, “clear” day (from 2.6 to 3.6 *dv*)

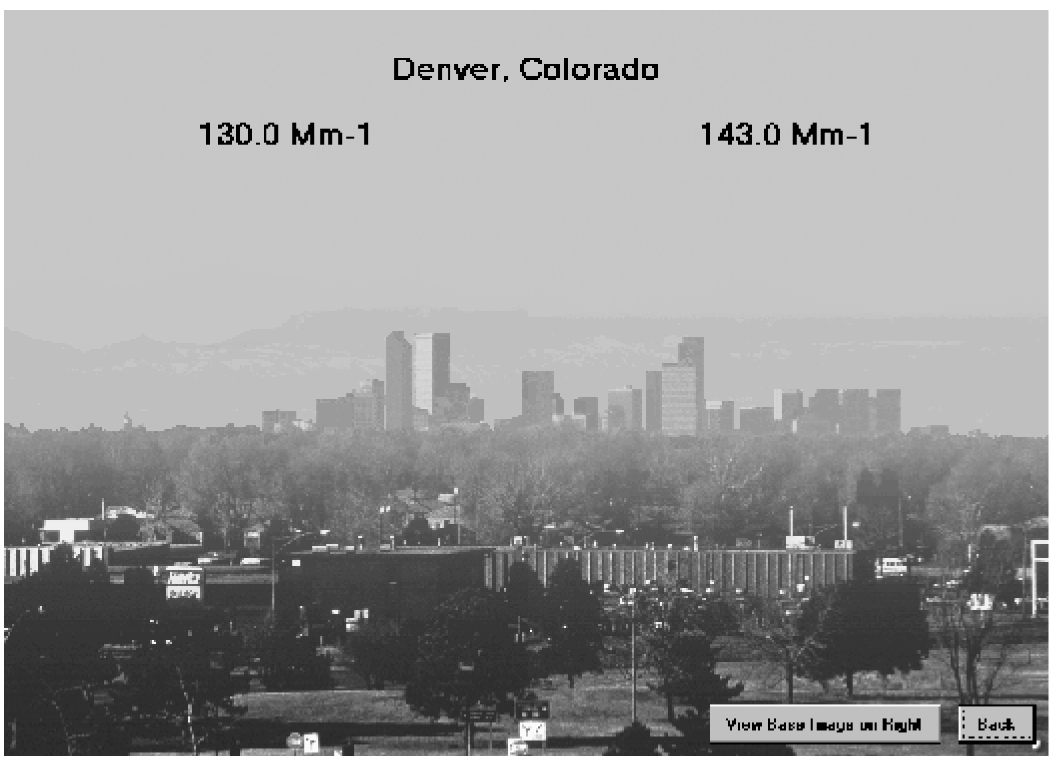

Figure 2d. Denver, Colorado, USA, “polluted” day (from 26 to 27 *dv*)

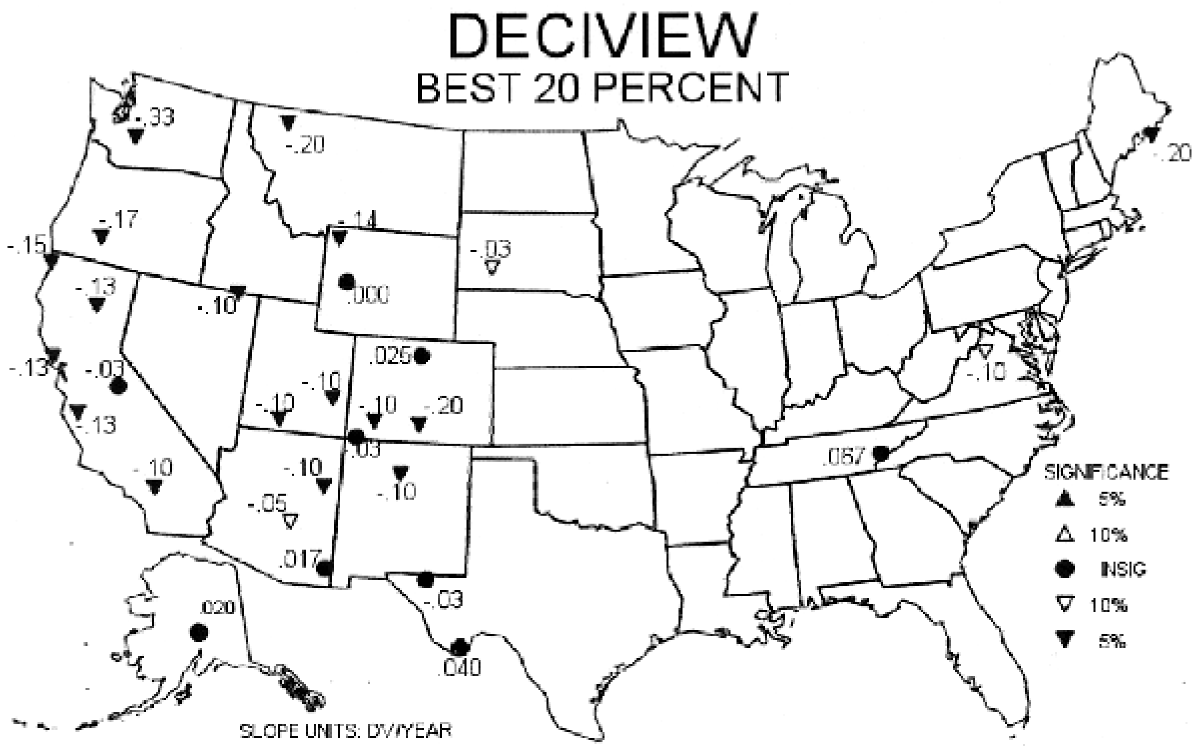

Figure 3a. Long-term IMPROVE aerosol sampling trends for the "cleanest" aerosol samples (in *dv*)

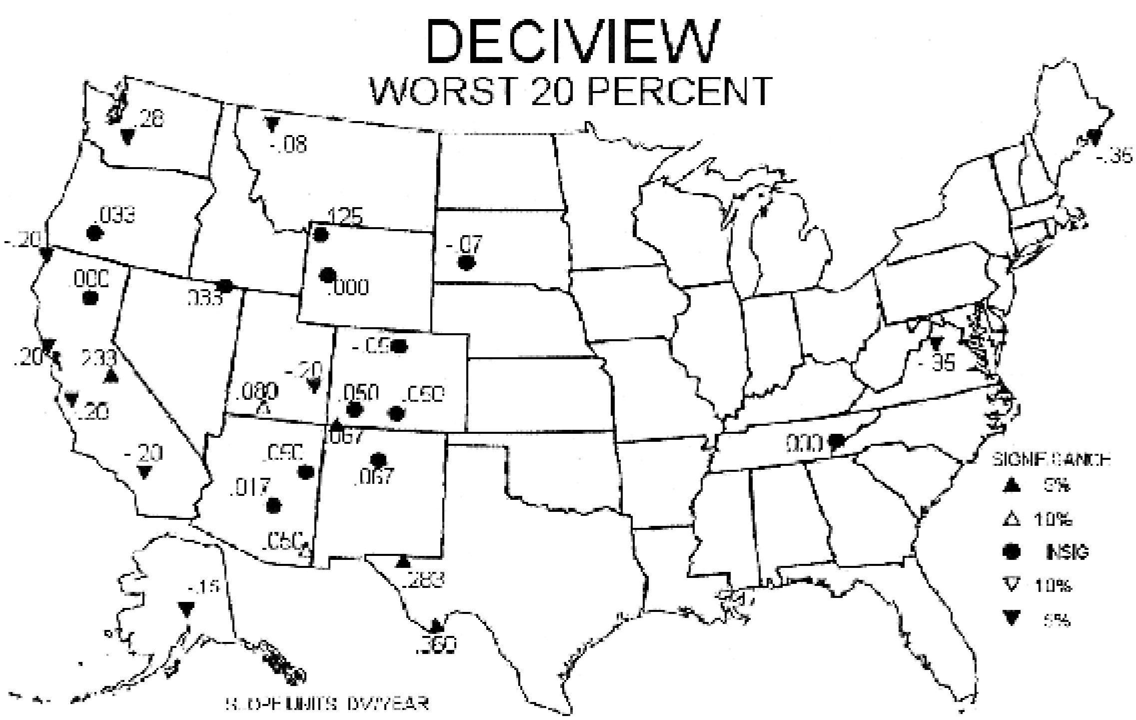

Figure 3b. Long-term IMPROVE aerosol sampling trends for the "dirtiest" aerosol samples (in *dv*)

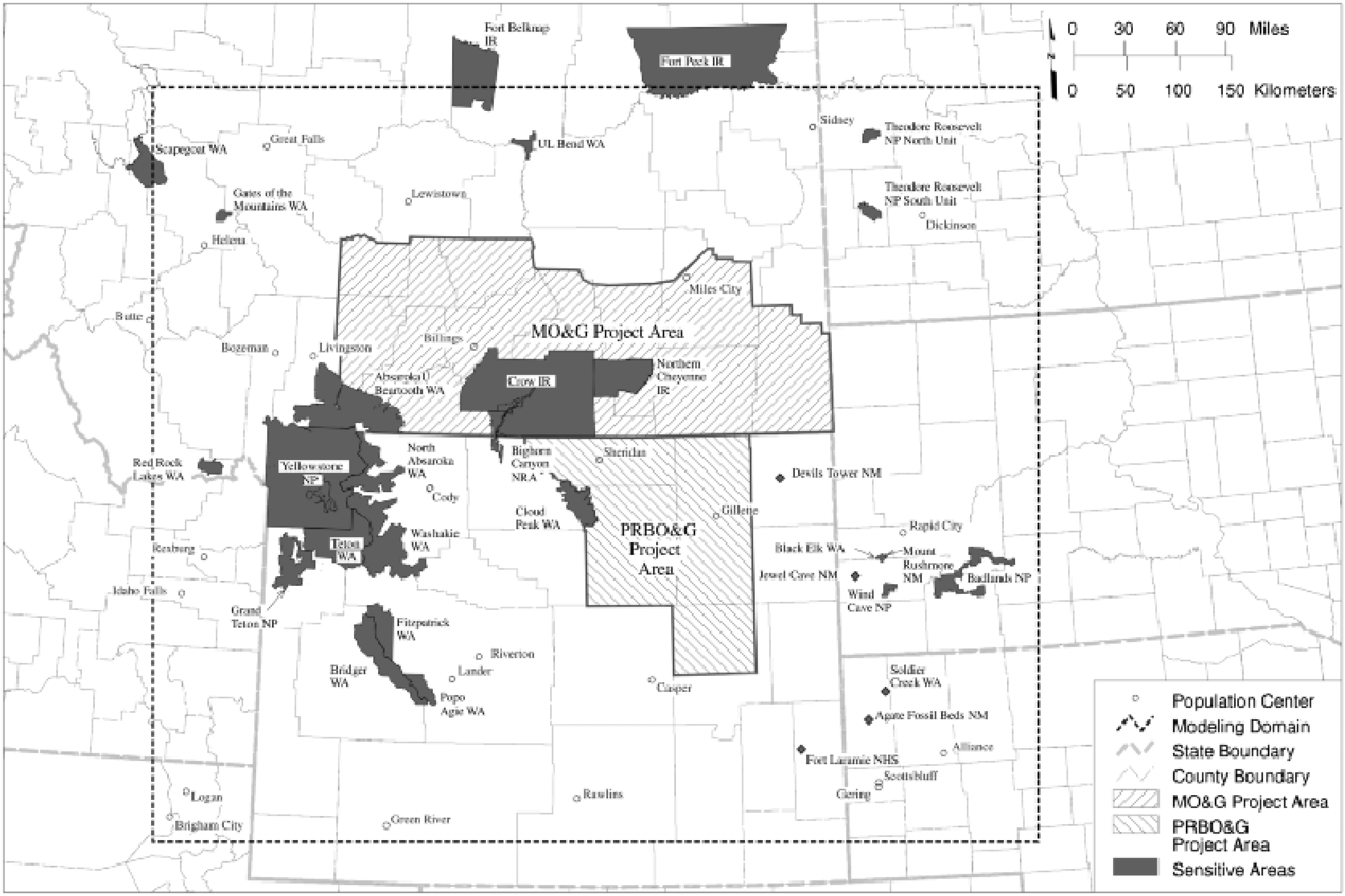

Figure 4. Montana/Wyoming coal-bed methane air quality impact analysis sensitive receptors